FRAGMENT HAZARD STUDY

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Sept. 1969

ABSTRACT

A mathematical model for estimating fragment risks of various ground ranges and orientations has been formulated and programmed for electronic data processing. The model uses experimental data on initial fragment fields and target vulnerability data as inputs. Fragment trajectories are solved by numerical methods from the equations of motion, providing terminal positions and ballistic properties computed. A subroutine prints out fragment density contours for the munition and contours of equal probability of damage for the munition/ target combination. In its present form the model is limited to consideration of the single round without environmental protection.

A limited parametric study of fragment terminal properties shows that large fragments can travel considerable distances and fall in low density fields. Though few in number, their terminal properties are at injury and damage-producing levels. Light fragments which are produced in large numbers travel much shorter distances and fall in higher density fields at terminal velocities which are significant primarily as personnel injury agents.

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INTRODUCTION

The Fragmentation Hazard Study initiated in April 1969 is aimed at applying engineering analysis, supplementary experimental efforts, and currently available data on fragmentation and damage criteria to the problem of estimating fragment hazards at explosive manufacturing and storage sites. It was originally conceived as a five-phase program with a total duration of about two years. This presentation reviews the overall program content and the results of the first four months of investigation.

OBJECTIVES

Primary objectives of the Fragment Hazard Study are:

I. To develop a methodology for estimating the risks of injury and damage from fragments on a probability basis, considering

- a wide range of human, mechanical and structural targets,

- all ground ranges and orientations from the store,

- simultaneous and repetitive detonations,

- various munition types and quantities, and

- open stores and protective environments.

II. To apply the developed methodology to determine levels of risk for a series of actual sites.

III. To conduct analytical and experimental studies required to fill gaps in current knowledge in support of the development of methodology.

MOTIVATION FOR THE STUDY

Initiation of this study was motivated by the recognition that current quantity-distance standards provide unequal fragment safety levels at various distances and that methods were needed for realistically assessing fragment hazards. It is seen, for example, that current quantity-distance standards are based on:

- $W^{1/3}$ scaling for Class 7 materials, and
- Quantity-independence for Class 3, 4, 5, 6 materials.

There is no reason to feel confident that fragment hazards would scale as the cube-root of quantity. Neither are fragment hazards expected to be quantity-independent.

Fragment risk levels are a function of:

- Case fragmentation patterns,
- Fragment initial velocities,
- Intra-round shielding within the store,
- Airblast induced acceleration,
- Fragment interaction during flight, and
- Injury or damage criteria for vulnerable targets.

Case fragmentation patterns and initial fragment velocities are a characteristic of the individual munition. Airblast effects are a characteristic of the individual munition which may have a cumulative effect in a store, depending on firing sequence. Intra-round shielding and fragment interaction are affected by munition characteristics, configuration of the store and firing sequence in the store. Injury and damage criteria are generally some function of fragment mass, terminal velocity, and impact angle. There is little likelihood that the net effect of these factors would either scale as $W^{1/3}$ or be quantity-independent. Means for estimating fragment hazards based on the physical phenomena of fragment generation, fragment flight and target response were recognized to be needed.

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PROBLEM APPROACH

The Fragment Hazard Study is outlined as a five-phase effort as follows:

Phase I: Establishment of Damage Levels and
              Damage Criteria for Targets of Interest

Phase II: Determination of Target Vulnerability
              from Detonation of Single Munitions in
              Open Stores

Phase III: Determination of Target Vulnerability
              from Detonation of Multiple Munitions
              in Open Stores

Phase IV: Modeling Fragment Mass, Velocity and
              Spatial Distribution for Enclosures
              Containing Large Munitions Stores

Phase V: Determination of Fragment Risk Levels
              at Explosive Sites

Implementation of this program involves application of engineering procedures to develop a logical scheme for estimating fragment hazards, including:

- analytical procedures, such as trajectory analysis to determine terminal positions and terminal ballistic properties of fragments,

- fragmentation test results for munitions, defining the initial spatial field of fragment masses and velocities, and

- vulnerability factors developed on weapons tests and other programs.

This is a milestone in the development of explosives safety standards to recognize the differences in scaling laws for fragment effects as contrasted with blast effects as contrasted with blast effects.

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PROGRAM STATUS

The current status of the overall program is as follows:

- The combined Phase I-II program is scheduled for completion before the end of October 1969. Formulation and programming of a mathematical model for computing fragment damage probability contours for the single munition are complete.

- Detailed work plans are completed for the Phase III study.

- General work statements are written for Phases IV and V.

Estimates indicate that the entire program can be completed by the end of fiscal year 1971.

CHARACTERISTICS OF THE FRAGMENT HAZARD MODEL

A mathematical model for computing damage probability contours for various munition/target combinations on a probability basis has been formulated and programmed for electronic data processing. The Phase II mathematical model, for which a simplified flow chart is shown as Fig. 1, is limited to the consideration of the single munition without environmental protection. The model is modular and can be refined in subsequent phases of the program to consider multiple munitions in various configurations, and environmental protection.

The Phase II model accepts as inputs:

- The spatial distribution of fragment masses and velocities for individual munitions, which are defined for each 5 deg sector of polar angle.

- "K-factors" for the individual munition, which express the relationship between fragment masses and projected areas for various munition types. These factors are needed to obtain projected areas for fragments in drag expressions for subsequent trajectory computations, and are not equivalent to the K-values used as coefficients in scaling formulae.

- Vulnerability criteria for targets of interest, in the form of mass-velocity relationships of impacting fragments.

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GENERATION OF                          PROBLEM EXECUTION
TERMINAL BALLISTIC
DATA FILE

┌──────────────────┐        ┌──────────────────────────────────┐
│ FRAGMENT AND DRAG│        │              INPUT               │
│   PARAMETERS     │        │        MUNITION & TARGET          │
│ ─ ─ ─ ─ ─ ─ ─    │        └──────────────────────────────────┘
│ MASSES           │
│ INITIAL VELOCITIES│
│ C_d = f(V)       │
│ k-FACTORS        │
└──────────────────┘

┌──────────────────┐        ┌──────────────────────┐
│ TRAJECTORY       │        │ INITIAL FRAGMENT     │
│ COMPUTATIONAL    │        │ FIELD DATA FOR       │
│ PROGRAM          │        │ SPECIFIC MUNITION    │
└──────────────────┘        │ MASSES, INITIAL      │
                            │          VELOCITIES, │
                            │ k-FACTORS            │
                            └──────────────────────┘

┌──────────────────┐  ┌─────────────────────┐  ┌──────────────────┐
│ FRAGMENT TERMINAL│  │ TERMINAL BALLISTIC  │  │ STORED INJURY AND│
│ BALLISTIC        │  │ PROPERTY STORAGE IN │  │ DAMAGE FUNCTIONS  │
│     PROPERTIES   │  │ THREE-DIMENSIONAL   │  │                  │
│ ─ ─ ─ ─ ─ ─ ─    │  │ MATRIX              │  │ MASS-VELOCITY    │
│ TERMINAL DISTANCE│  │                     │  │    CRITERIA       │
│ TERMINAL VELOCITY│  │        V_o    M  α  │  │   M    P_2  P_1  V│
│ IMPACT ANGLE     │  │                     │  │                  │
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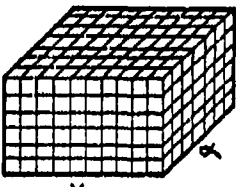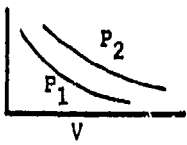
Terminal Ballistic Property Storage axes: V_o, M, α

Mass-Velocity Criteria axes: M vs V, curves P_2, P_1

┌──┐
│ VULNERABILITY DISCRIMINATOR & SORTING ROUTINE   │
│ ─   │
│ SELECTS DAMAGING FRAGMENTS & SORTS ON TERMINAL   │
│ DISTANCE FOR EACH POLAR ANGLE   │
└──┘

┌──────────────────────────────────────┐
│ INJURY/DAMAGE PROBABILITY   │
│ COMPUTATIONAL ROUTINE ─ ─ ─ ─   │
│ FRAGMENT DENSITIES,   │
│ PROBABILITIES FOR EACH POLAR ZONE   │
└──────────────────────────────────────┘

┌──────────────────────────────────────┐
│ CONTOUR PRINTING ROUTINE   │
└──────────────────────────────────────┘

┌──┐
│   OUTPUT   │
│ ISOPROBABILITY CONTOURS FOR INJURY/DAMAGE,   │
│ ISODENSITY FRAGMENT CONTOURS   │
└──┘

Fig 1 FLOW CHART
PHASE II FRAGMENT HAZARD MODEL

Outputs of the model include:

- o Fragment density contours showing distances at all polar orientations to isodensity lines. Contours can be printed for "all fragments" or for various classes of fragments.

- o Injury/damage probability contours, showing ground distances at all polar orientations to isoprobability or "equal risk" curves for various munition/target combinations.

Large quantities of terminal ballistic property data are used in developing these outputs. These data are generated by numerical methods from the equations of motion for the fragments. Since these computations represent the bulk of the computational burden involved in exercising the model, a terminal ballistic data file has been generated which covers the range of fragment masses, initial velocities, initial velocity angles, and k-factors to be encountered in exercising the model. Terminal ballistic properties for trajectories which are common to many polar angles and munition types are computed only once, stored in a computer data file, and retrieved as needed for solving specific vulnerability problems.

Elements of this model include the following:

- **Fragment and Drag Parameters**

A series of twenty classes of fragment masses, eight velocity classes, eighteen initial velocity classes, and two k-factors were selected for generation of the file of terminal ballistic data. These parameters cover the range of values encountered in the munitions selected for exercising the model in Phase II.

- **Trajectory Computational Routine**

This routine is used to compute the requisite terminal ballistic properties of individual fragments--terminal distances, terminal velocities, and impact angles. Formulation of the equations of motion includes consideration of the drag coefficient as a function of fragment velocity.

- ## Terminal Ballistic Data File

Terminal ballistic data for fragments are stored in a computer file in a manner which can be likened to a three-directional matrix as shown in Fig. 1. Terminal properties of a fragment are retrieved for individual problem execution from cells corresponding to the actual masses (M), initial velocities (V_o) and initial velocity angles (α). As set up, the model uses linear interpolation among the parameters M, and V_o wherever fragment parameters for the individual munition differ from those used in generating the terminal ballistic data file.

- ## Stored Injury and Damage Functions

Injury and damage functions define mass-velocity relationships for various probabilities of damage or injury.

- ## Vulnerable Fragment Discriminator and Sorting Routine

From among all munition fragments this routine selects terminal ballistic properties of fragments whose mass-velocity relations are above injury or damage levels and sorts them according to terminal distance. This is done successively for each 5 deg increment in polar angle on the munition.

- ## Injury/Damage Probability Computational Routine

Fragment densities and injury/damage probabilities are computed in this routine, bringing land and target areas into consideration. This routine is also exercised successively for each 5 deg increment in polar angle on the munition.

- ## Contour Printing Routine

This routine prints contours of equal fragment density and equal injury/damage probability for the various combinations of munition and target.

PROBLEM EXECUTION

The Fragment Hazard Model will be exercised for all combinations of the following single munitions and targets on the Phase II program:

Munitions	Targets
• 500 lb M82 Bomb	• Standing Personnel
• 750 lb M117 Bomb	• Open Bomb Store
• 105mm Howitzer Shell M1	• Open Shell Store
• 155mm Howitzer Shell M107	• Vital Building
• 175mm Gun Shell M435	• Parked Aircraft
• 5 in./38 Projectile MK 49	• In-Flight Aircraft
• 8 in./55 Projectile MK 24	• Moving Automobile

Sample exhibits of outputs obtained in exercising the model for the case of the 500 lb M82 bomb with standing personnel as the target are shown in Figs. 2 to 4. Total fragment density contours, considering all fragments produced in the detonation of a single bomb, are shown in Fig. 2. Injurious fragment density contours considering only those fragments whose terminal mass-velocity relationships are above the threshold of serious injury for standing personnel, are shown in Fig. 3. Isoprobability contours for serious injury to standing personnel are shown in Fig. 4. The latter family of curves provide data for selecting separation distances for various levels of risk of serious injury to standing personnel. The families of curves in Figs. 2 to 4 reflect the types of outputs obtainable for various munition/target combinations by exercising the Fragment Hazard Model in its present form.

INJURY/DAMAGE CRITERIA INPUTS

Injury/damage functions of the form shown for standing personnel in Fig. 5 are being incorporated into the Fragment Hazard Model. The threshold of serious personnel injury from fragment impact was selected from this family of curves as the personnel vulnerability criteria and all fragments having
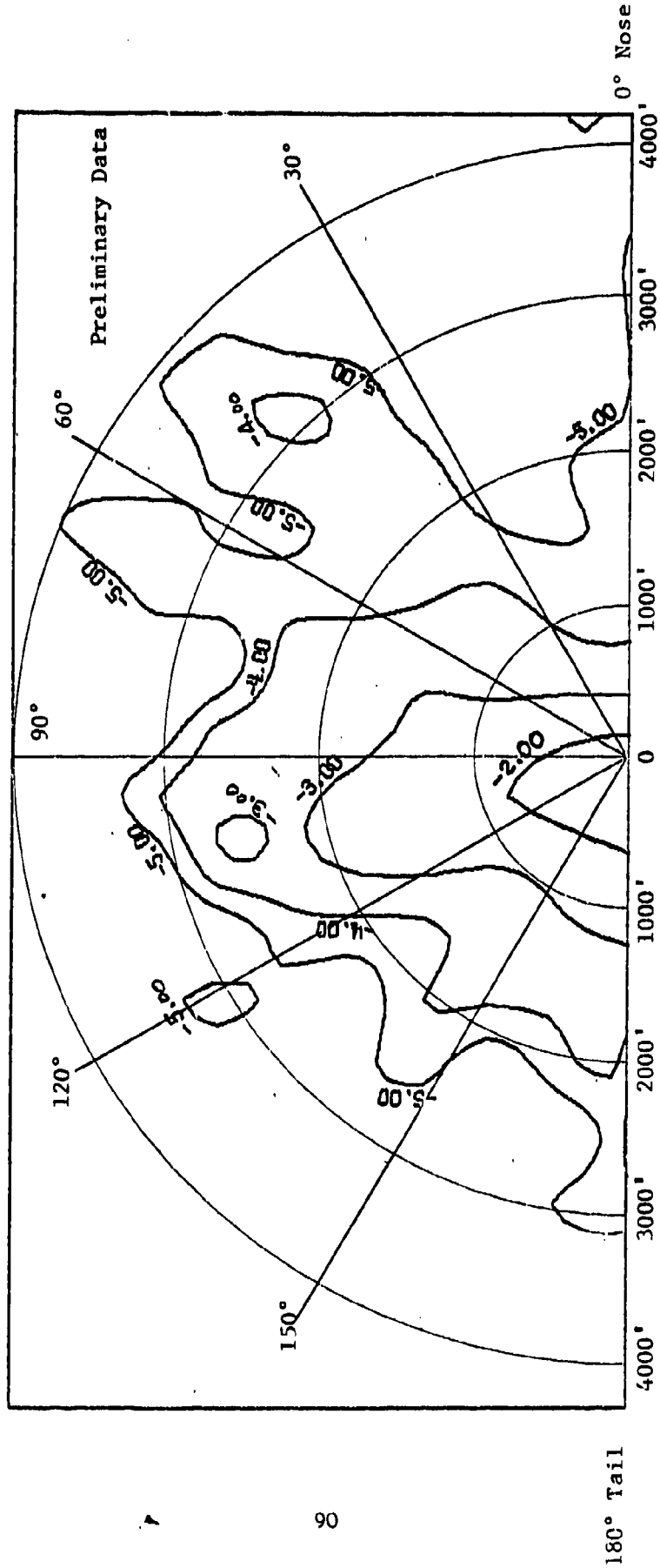
Fig. 2   FRAGMENT DENSITY CONTOURS - AIR FRAGMENTS
500 LB M82 BOMB - SINGLE MUNITION

Note: Fragment Density = 1.0×10^a Fragments per sq ft
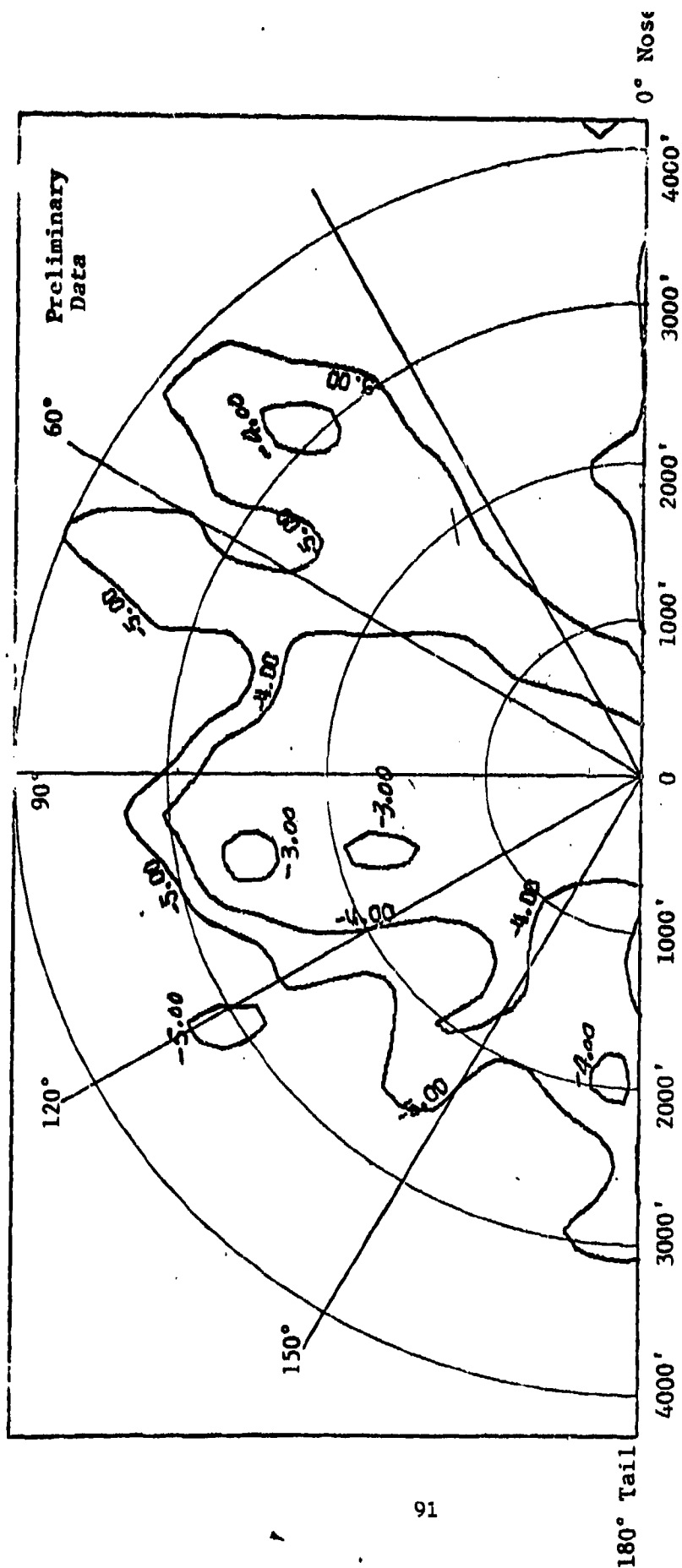where exponent a is shown on contour line.

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Fig. 3 FRAGMENT DENSITY-SERIOUSLY INJURIOUS FRAGMENTS
500 LB M82 BOMB-SINGLE MUNITION

Note: Fragment Density = 1.0×10^b Fragments per sq ft
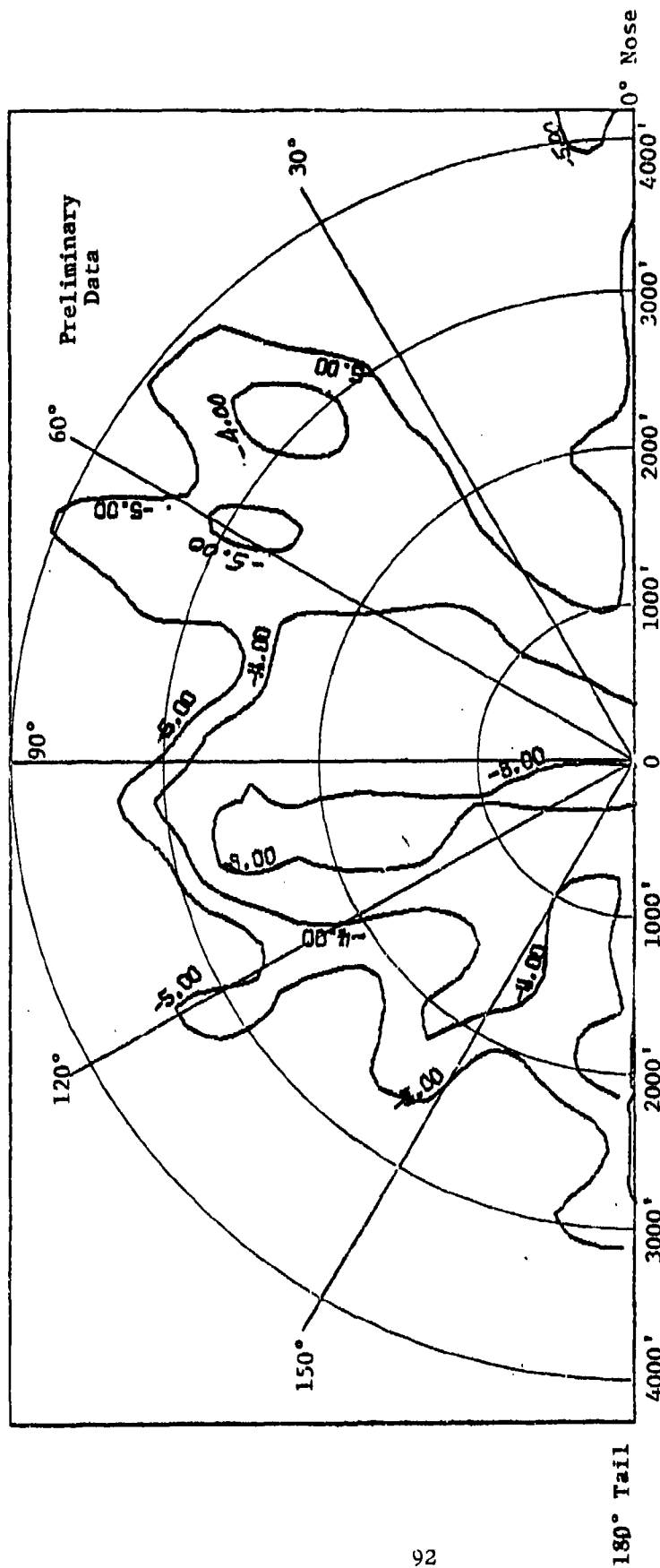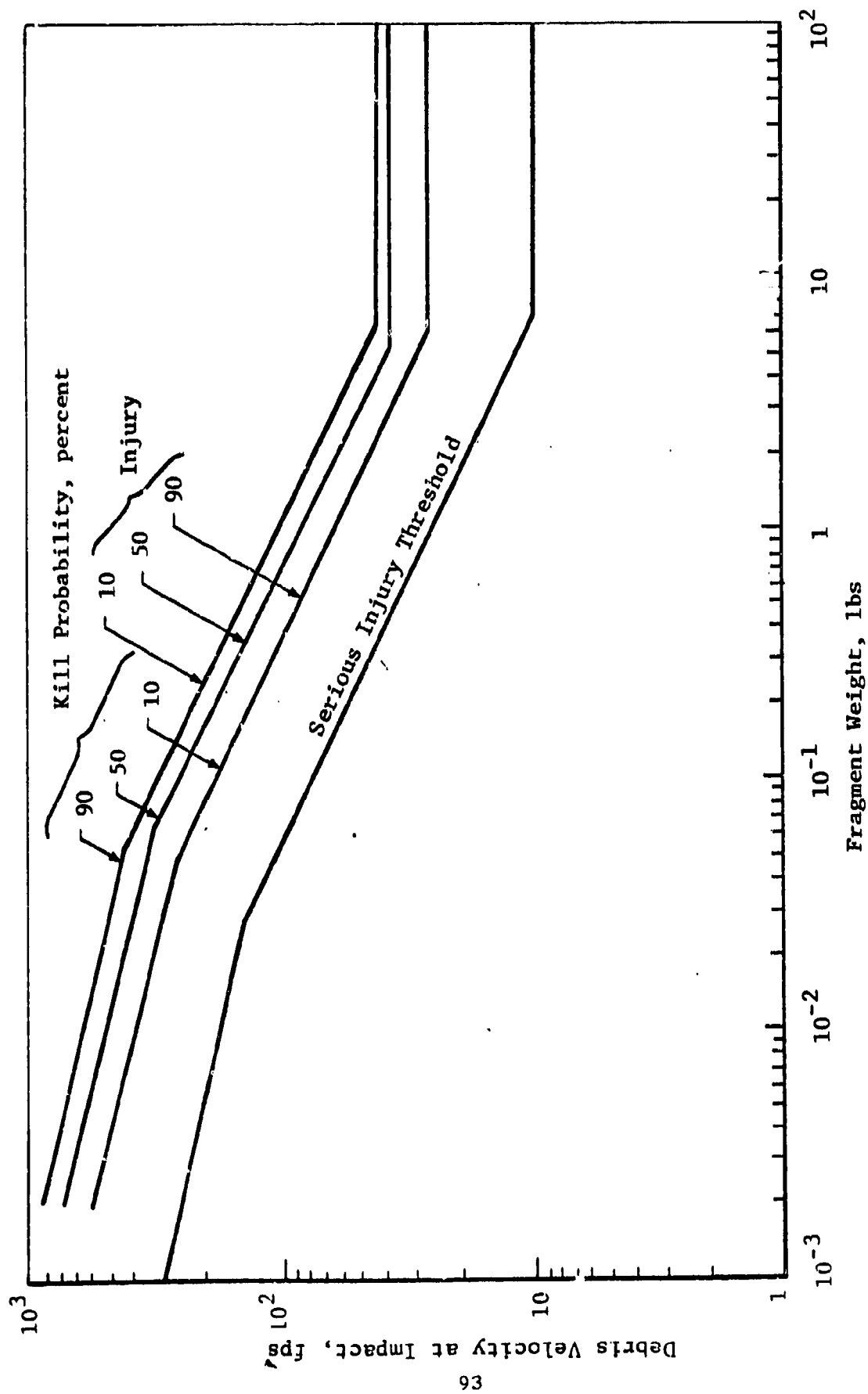where exponent b is shown on contour line

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Fig. 4 SERIOUS PERSONNEL INJURY PROBABILITY CONTOURS
500 LB M82 BOMB-SINGLE MUNITION

Note: Fragment Density = 1.0×10^{c} Fragments per sq ft.
where exponent c is shown in contour line.

Fig. 5 PERSONNEL RESPONSE TO FRAGMENT IMPACT (Abdomen and Limbs)

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mass-velocity relationships in excess of threshold level were included in developing vulnerability contours. It is noted that the contours then represent "serious injury and lethality" inasmuch as some fragments may be sufficiently above the serious injury threshold level to be in the mixed injury/ lethality range.

Serious injury threshold curves for fragment impact on abdomen and limbs, thorax, and head are plotted together in Fig. 6. The curve for abdomen and limb injury was applied in the current model formulation because, i) these members represent a greater portion of body projected area than the thorax and ii) it represents a lower and more conservative threshold in the mass-range of most munition fragments--under 0.2 lb. The total projected area of the human body, as measured normal to the fragment impact angle, was taken as the target area in computing injury probabilities.

FRAGMENT TRAJECTORY CHARACTERISTICS

A corollary exercise in variation of trajectory parameters was conducted in preparing the trajectory computational routine, the results of which are shown in Fig. 7-13.

The general trajectory form, point of maximum trajectory heights, and terminal distances of a series of high velocity, low angle fragments of various weights are shown in Fig. 7. It is seen that, for these drag-influenced fragments, the point of maximum trajectory height is reached at about 65 percent of terminal distance for the lighter fragments and about 75 percent of terminal distance for the heavier fragments. Terminal velocity angles, at impact, have been found to be very steep, generally greater than 80 deg.

The relationship between terminal trajectory distance and fragment weight for light fragments with a constant initial velocity and various initial velocity angles is shown in Figure 8. It is seen that maximum terminal distance corresponds.
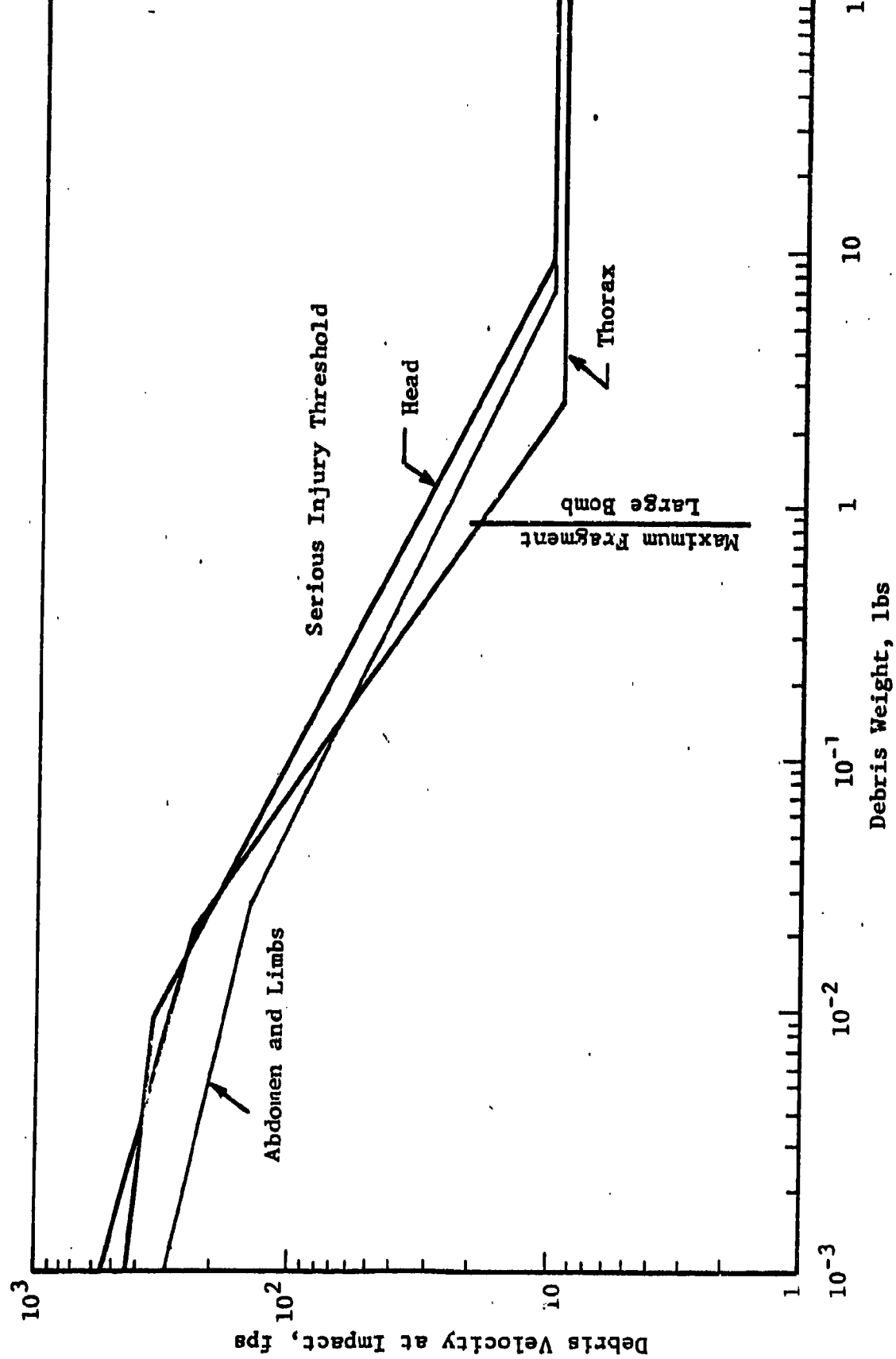
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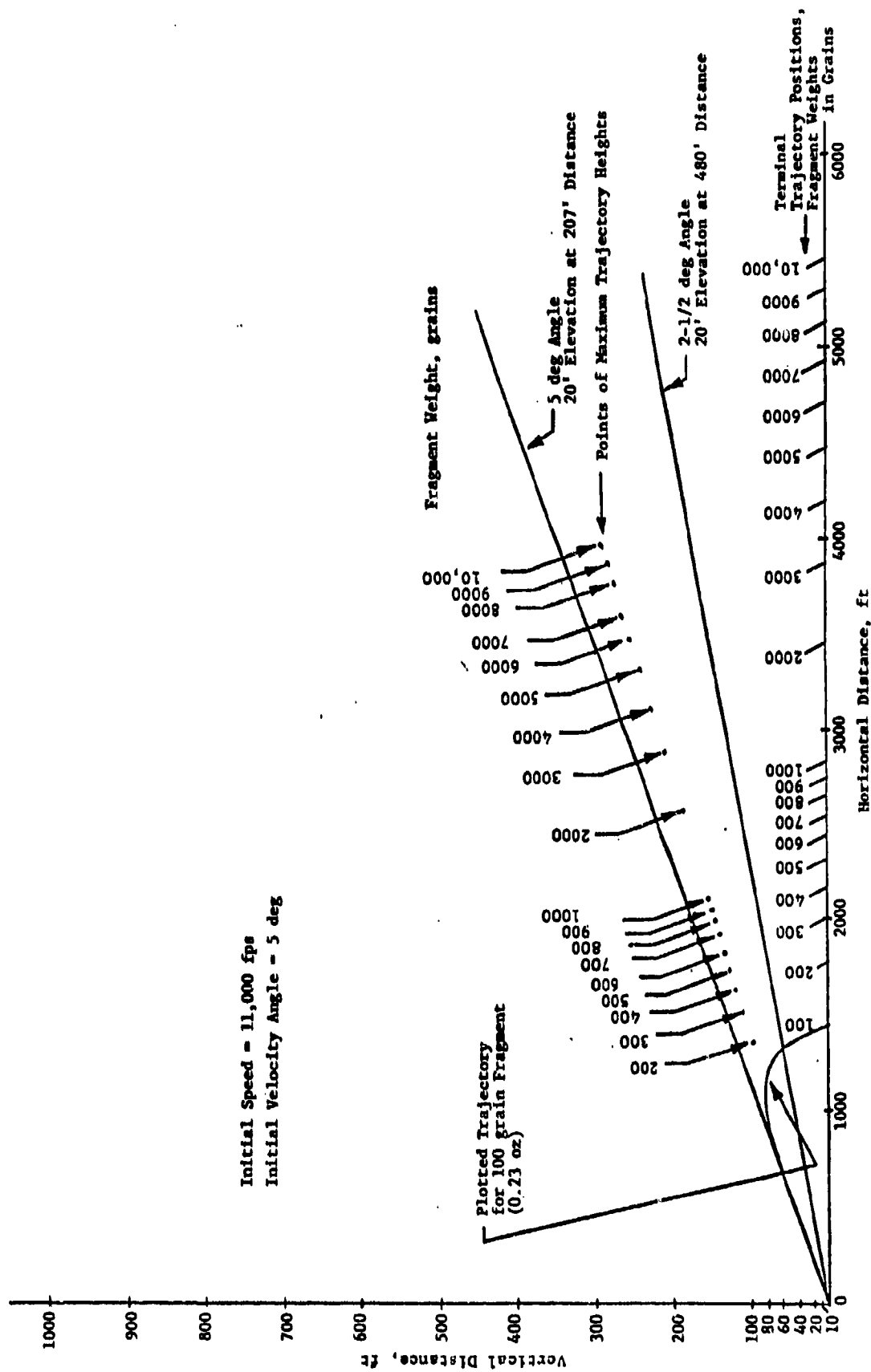Fig. 6 PERSONNEL RESPONSE TO FRAGMENT IMPACT

Fig. 7 SELECTED FRAGMENT TRAJECTORY CHARACTERISTICS HIGH VELOCITY, LOW ANGLE FRAGMENT

to an initial velocity angle of 20 de   From the horizontal
terminal distances are seen to be far more sensitive to varia-
tions in fragment weight than to variations in initial eleva-
tion angle. It is also seen that the light fragments from
munitions do not travel to extreme distances, even with very
high initial velocities. A comparable chart for heavy frag-
ments is shown in Fig. 9. Though relatively few in number,
heavy fragments with high initial velocities can travel great
distances. When considering these distances in the vulner-
ability context it must be remembered that an initial frag-
ment velocity of 11,000 ft/sec is very high and that fragment
densities at these distances are low.

The relationship between terminal distance, initial veloc-
ity and fragment weight, with initial velicity angle held
constant, is plotted in Fig. 10. Terminal distances for heavy
fragments are seen to be more sensitive to variations in
initial velocity than light fragments.

Relationships between initial velocity, terminal velocity
and fragment weight are shown in Fig. 11, with terminal dis-
tances noted at the end points of the curves. It is noted
that terminal velocities of light fragments are quite low
and are at levels where they are primarily hazards to personnel
in the open at closer ranges. Velocity attenuation for heavy
fragments is also seen to be very considerable. What appears
to be an anomaly here, where fragments with the higher initial
velocities have lower final velocities, is explained by the
fact that, with longer trajectories they are subjected to
drag forces for longer durations.

Terminal velocities for light fragments, with low initial
velocity angles, plotted in Fig. 12, are also seen to be more
sensitive to variation in fragment weight than to initial
elevation angle. A similar trend is observed for terminal
velocities of heavy fragments, as seen in Fig. 13. Terminal
velocities in these figures are a result of the net effects
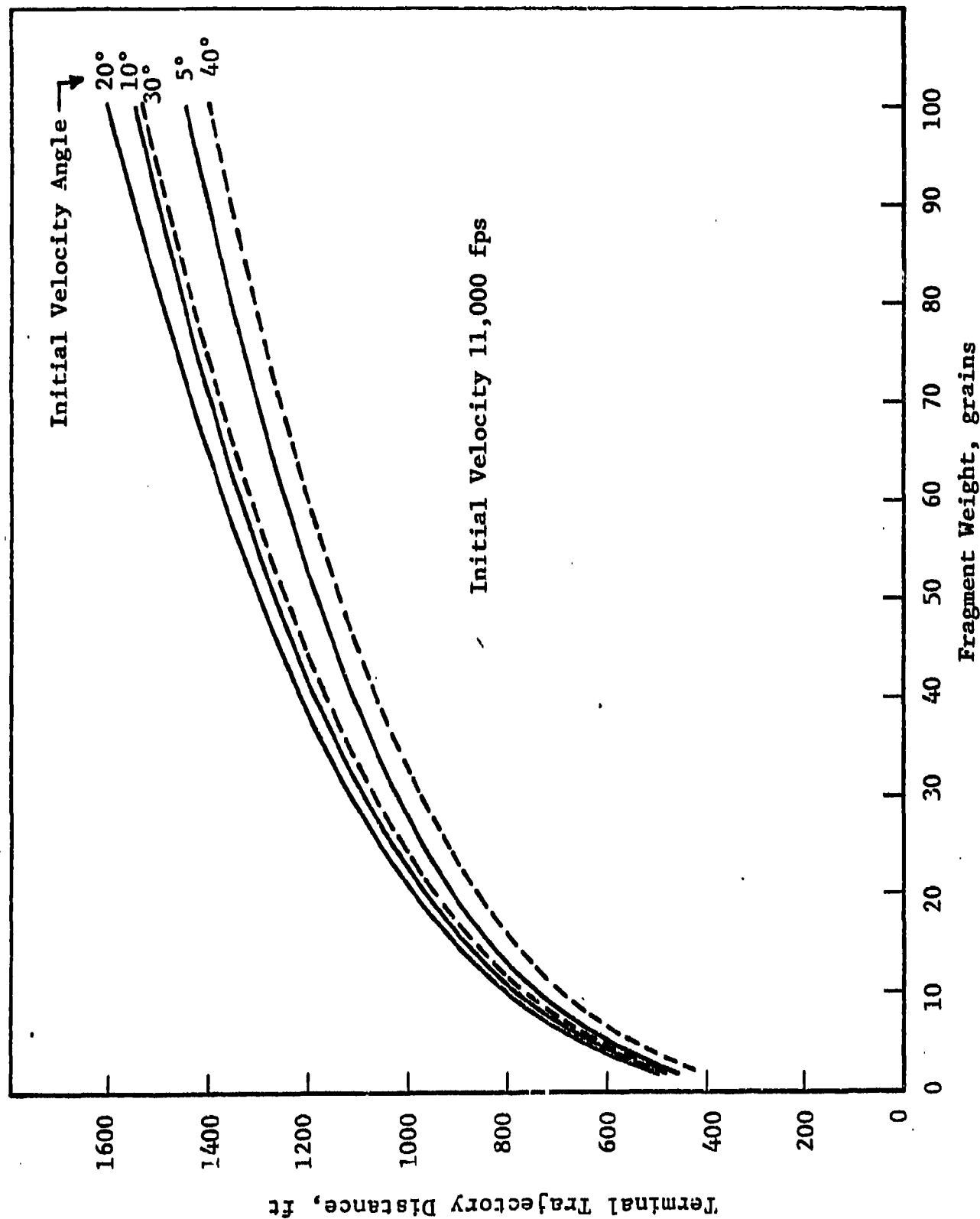of both drag and gravity.
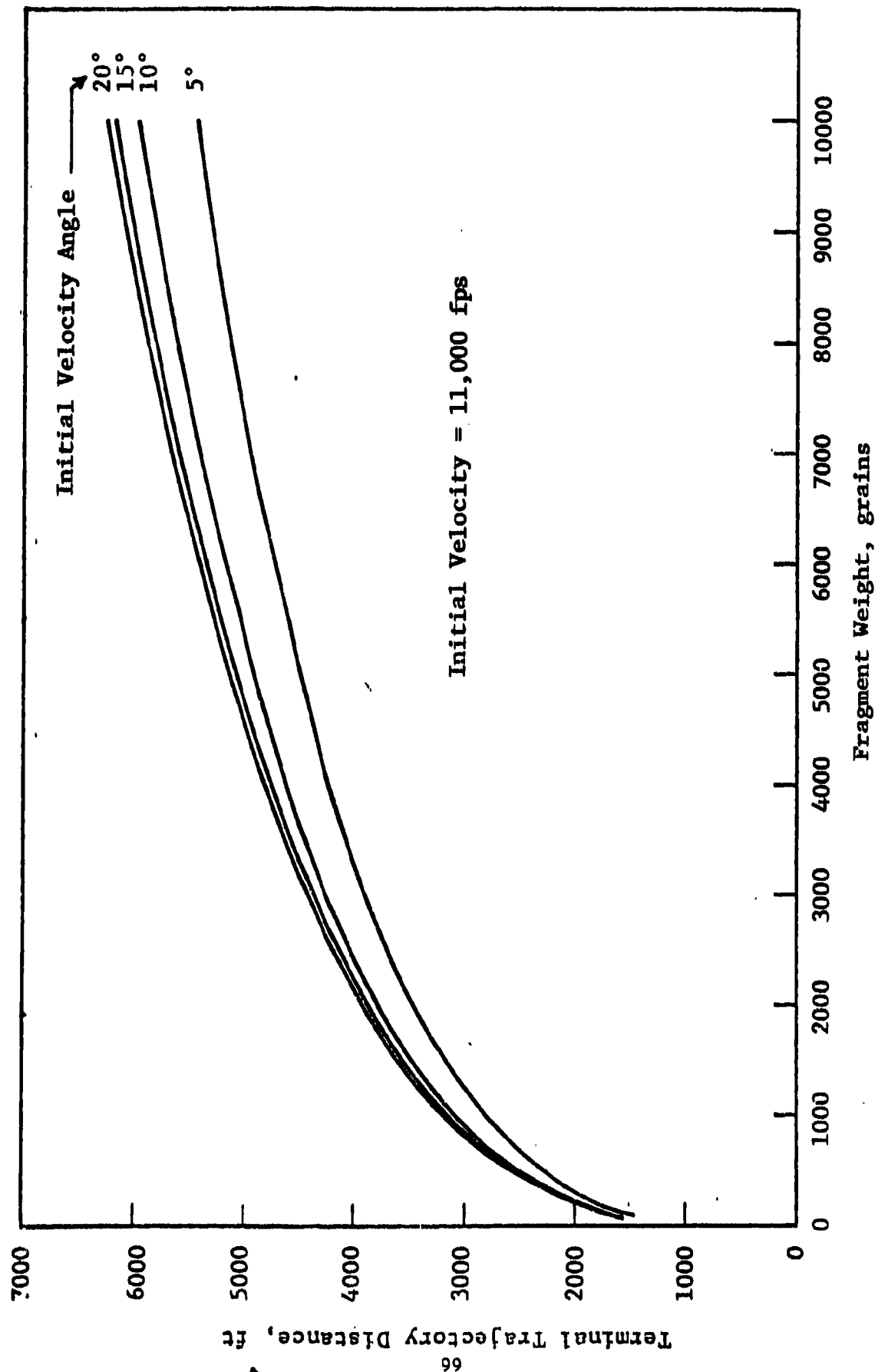
Fig. 8 WEIGHT VS TERMI'L DISTANCE - LIGHT FRAGMENTS
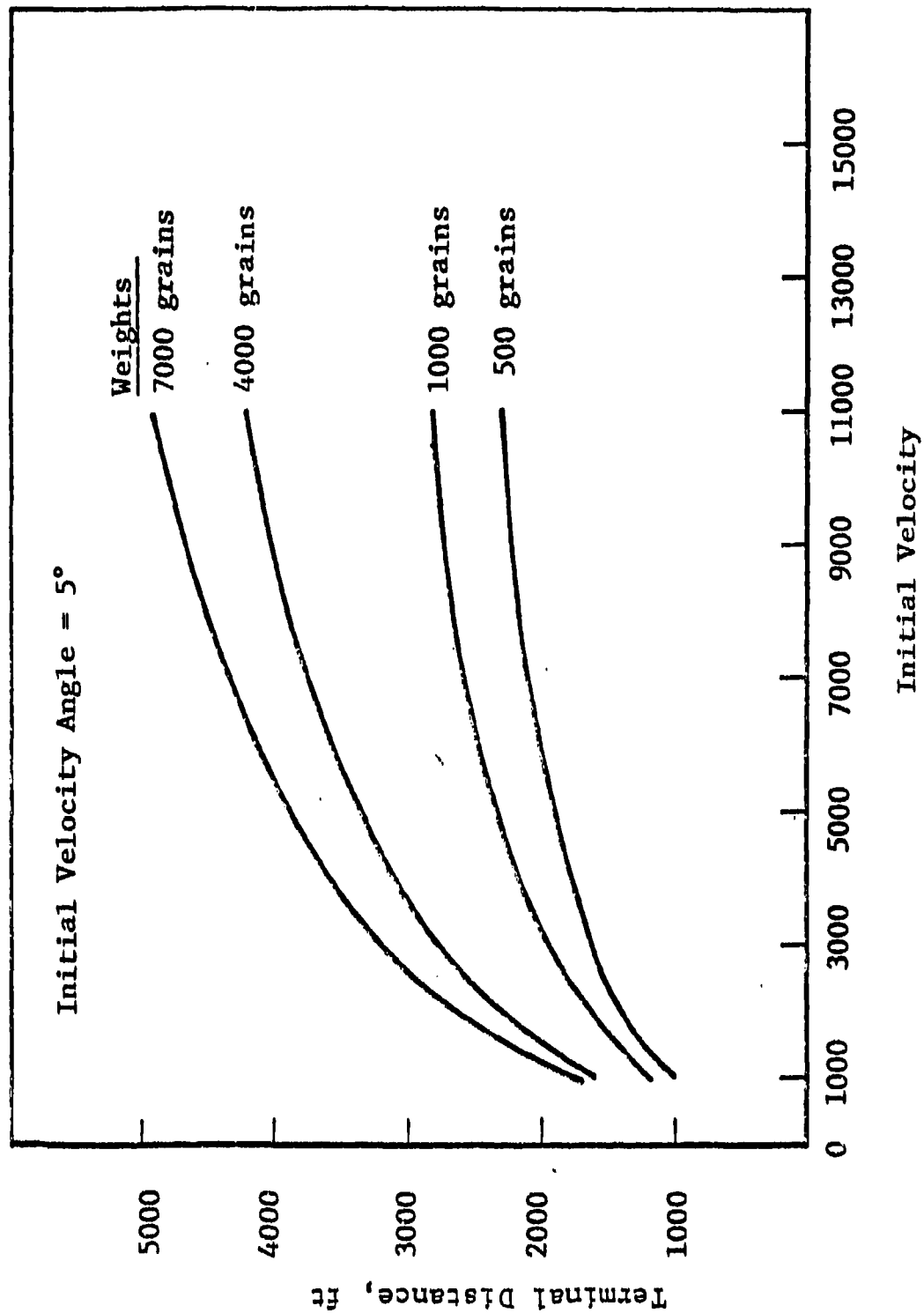
Fig. 9 WEIGHT VS TERMINAL DISTANCE – HEAVY FRAGMENTS

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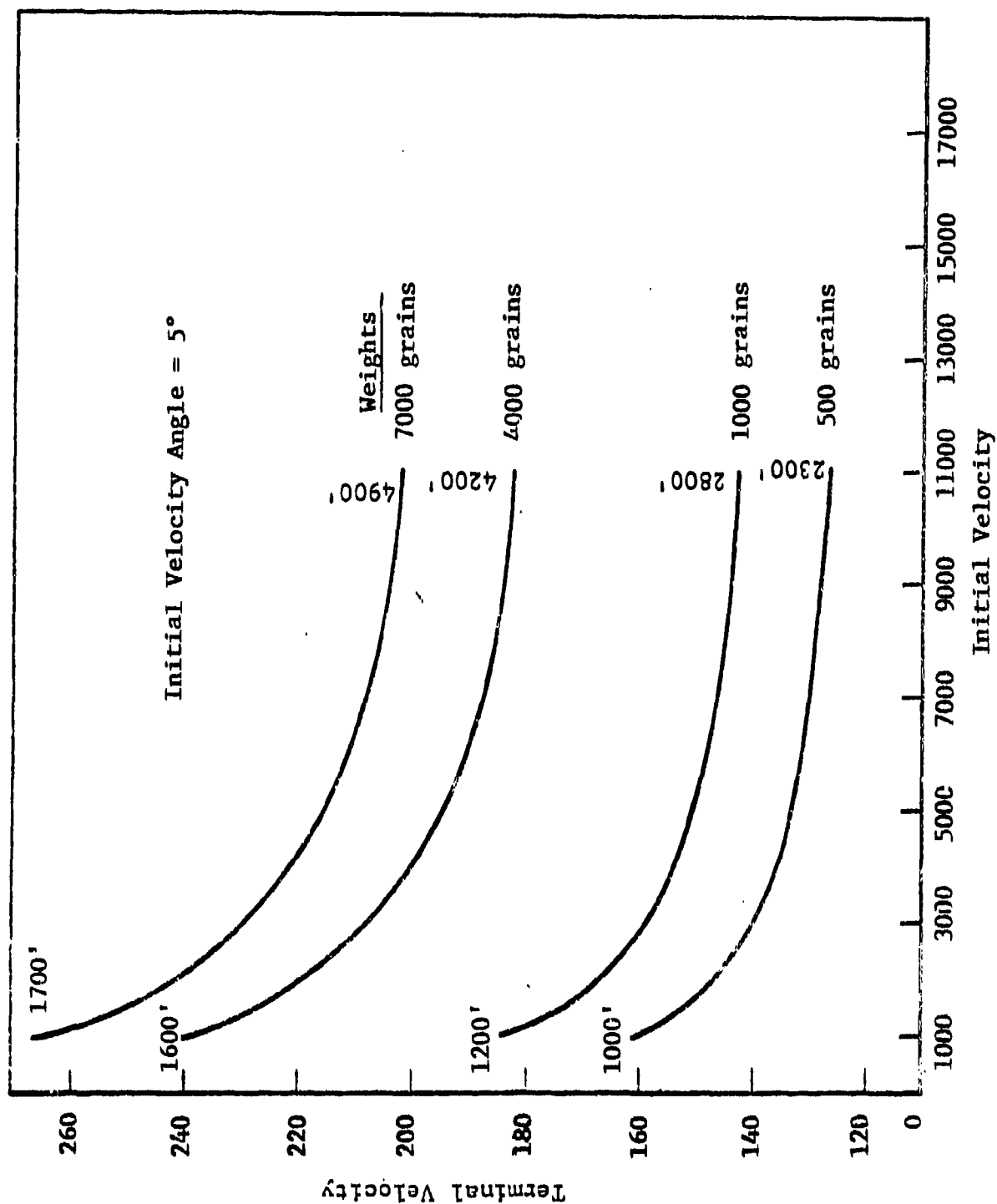Fig. 10   INITIAL VELOCITY VS TERMINAL DISTANCE FOR VARIOUS WEIGHTS

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Fig. 11   INITIAL VELOCITY VS TERMINAL VELOCITY FOR VARIOUS WEIGHT FRAGMENTS
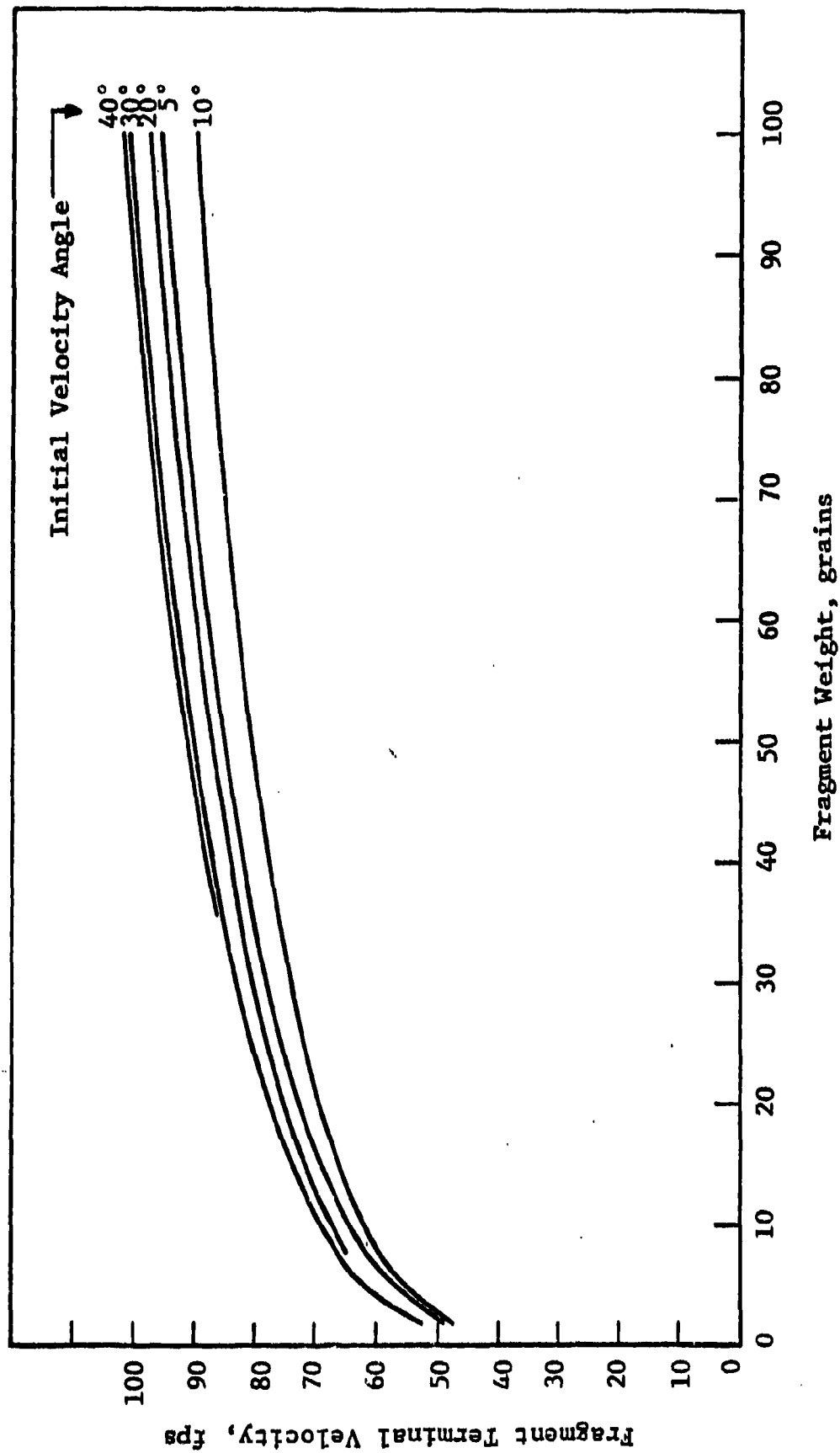
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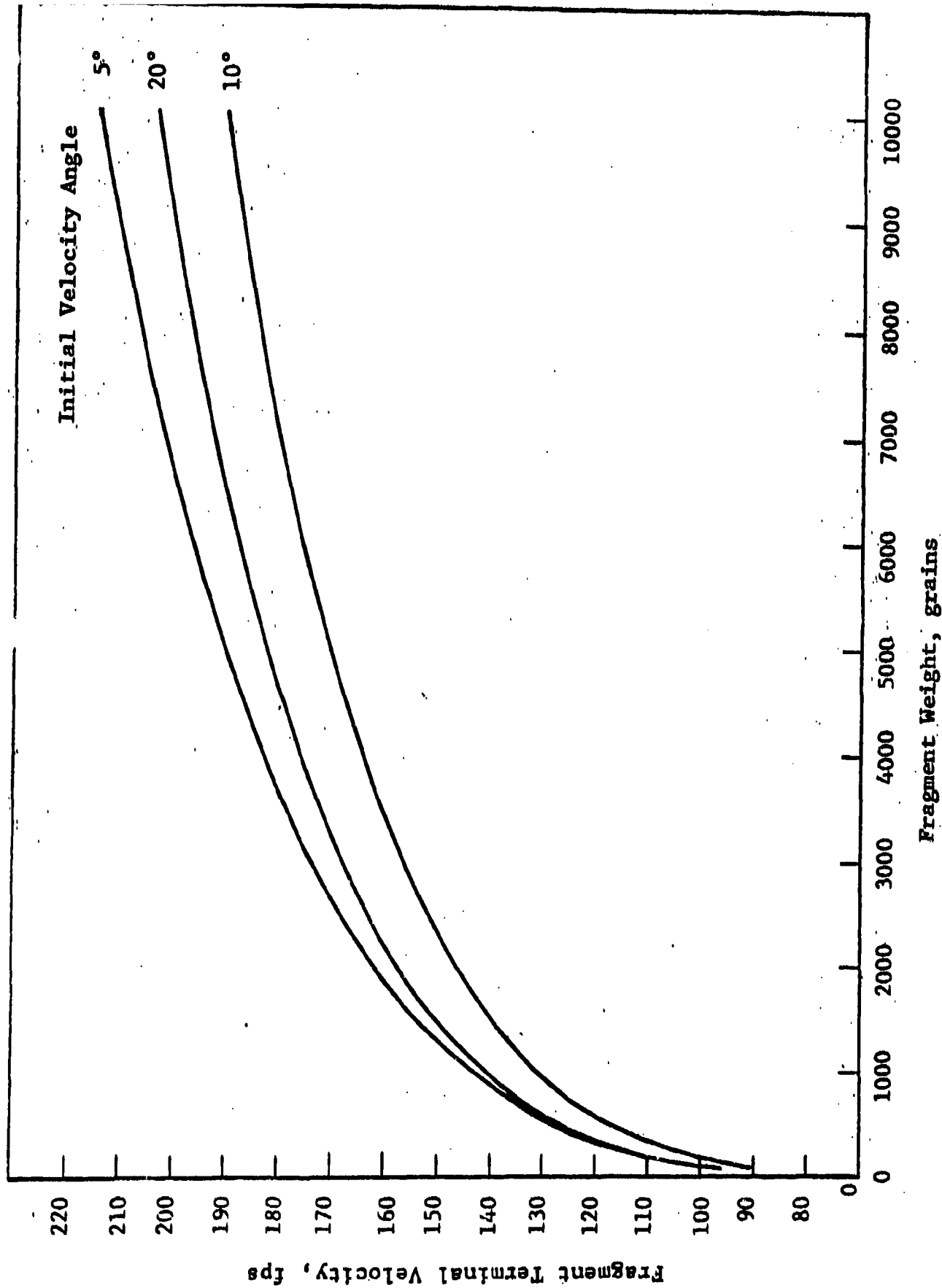Fig. 12   WEIGHT VS TERMINAL VELOCITY - LIGHT FRAGMENTS

Fig. 13   WEIGHT VS TERMINAL VELOCITY - HEAVY FRAGMENTS

SUMMARY

A limited parametric study of fragment trajectories has shown that:

- Most munition fragments have small mass, travel relatively short distances, fall in regions of high fragment densities with low velocities.

- Though few in number, large fragments travel much further where they fall in low density field.

Using the technique of trajectory analysis, a mathematical model has been developed for estimating injury/damage contours for various combinations of targets and single munitions. It has been found possible to confine the computational burden of trajectory computations to essentially a "setup" operation through storage of terminal ballistic data in a computer data file for ultimate retrieval in solving problems.

Procedures have been outlined for extending the model to the case of the multiple munition in open stores. For the case of the nonmass detonating munition store the problem in considered one of computing injury/damage probabilities at linearly-increasing fragment densities.

Extending the model to the case of the mass-detonating munition store is a more complex problem, involving the following basic considerations:

- Accidental detonation of one munition leads in general to nonsimultaneous detonation of other units.

- Fragment fields from more than one munition will partially interfere mutually to preclude simple point-for-point addition of single munition fragment maps.

- Fragment from a covered munition cannot initially enter the effective fragment field prior to detonation of the covering munition.

- Some airblast induced acceleration of fragments may result from nonsimultaneity of detonation.

With these considerations in mind the fragment field for the mass-detonating munition becomes a linear multiple of the field for the individual round, plus airblast induced acceleration effects, less the effects of intra-round shielding and fragment interaction.

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Discussion of the Paper

INVESTIGATION INTO FRAGMENT AND DEBRIS HAZARDS
FROM EXPLOSIONS

Attendee interest was expressed in the variations in trajectory parameters. Additional exhibits concerning munition fragment behavior were shown. Though exhibits these were not included in the technical presentation before the general session, they have been included in the foregoing paper to provide continuity in the subject matter.

Extensive attendee interest was shown in applying the Fragment Hazard Model to assess the risks involved in missile explosions. It was explained that the Fragment Hazard Model contains a ballistic trajectory computational routine and its exercise requires input data on the spatial distribution of fragment masses and initial velocities. The air-to-ground rockets are immediately amenable to treatment in the model since:

- the spatial distributions of masses and initial velocities have been measured,

- trajectories for these fragments are essentially ballistic, and

- characteristic "k-values" expressing the relationship between fragment mass and projected area have been measured.

It was shown that several differences exist between conditions for the explosion of large missiles and the ballistic Fragment Hazard Model in its present form:

- The munition was considered in a standing position, on end, in some of the missile problems posed; whereas, the Fragment Hazard Model considers the munition lying on its side. This does not preclude similar analytical treatment of ballistic fragments, though some modification of the model would be required by the change.

- In the larger missiles, skin fragments in large sizes may be generated whose trajectories may be influenced by lift. The model does not include provisions for considering lift.

- The missile explosion was said to sometimes follow partial combustion of the fuel. This could result in convection currents which could further influence the response of skin fragments susceptible to lift.

The question of potential applicability of the model to the problem of assessing risks to observers also arose. The model can be exercised to obtain data for evaluating observor risk levels, providing the required input data is available. Assuming observor sites to be relatively close-in, neglect of lift effects on trajectories of skin fragments might be permitted.

Interest shown in fragment behavior from past incidents prompted the showing of additional exhibits as follows:

- Correlation between maximum fragment distance and equivalent weight of explosives, which is shown in Fig. 1 for a large number of explosions. The extreme scatter of data points stems from dissimilarities in types of explosion, structures involved, and environments.

- Distribution pattern for concrete fragments from a Pantex Ordnance Plant explosion test. (Figs. 2-4) The test provided a thoroughly documented record of weights and terminal positions of about 35,000 fragments with a total weight of about 85,000 lbs. The missile map, Fig. 2, shows fragment densities of the order of one per 2500 sq ft were observed locally as far as 1400 ft from the detonation. The decidedly unsymmetrical pattern resulted from the environmental configuration. The overall dispersion of fragments is expressed in Fig. 3, with values being computed on the basis of circumferential areas. Variations in mean fragment weight with ground range is plotted in Fig. 4.